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The impact of conflicting spatial representations in airborne unmanned aerial system sensor control

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Abstract

The purpose of this study is to extend the basic research findings on spatial representations to a unique application area and extend the small number of applied research studies in this general area to a more robust, Navy-specific application set (i.e., Unmanned Aerial Systems). In this study, participants assumed the role of a sensor operator for an unmanned aerial system (UAS) simulation while riding in the fuselage of an airborne Lockheed P-3 Orion. The P-3 flew a flight profile of intermittent ascending, descending, and turning profiles (in strict accordance with an emphasis on safety of flight) to induce a maximum level of spatial discordance to the sensor operator screen where the participant tracked simulated targets. Participants also performed trials on the ground with the laptop-based UAS sensor operator simulation to establish baseline performance. In a counterbalanced design, the participants performed trials while airborne and on the ground. The multiple frames of reference for the participant induced spatial discordance and an overall decrease in tracking performance compared to trials during straight and level flight and ground baseline trials.

The impact of conflicting spatial representations in airborne unmanned aerial system sensor control

Emerging concept of operations (CONOPs) for Unmanned Aerial System (UAS) employment for the US Navy calls for the potential control of UAS while airborne, such as controlling a broad area maritime surveillance (BAMS) UAS from an airborne P-8A or an unmanned carrier-launched surveillance and strike (UCLASS) UAS from a fighter-class aircraft. The utility of pairing these two types of aircraft is primarily to reduce the distance of the UAS and control station, thus reducing latency of control input and increasing bandwidth for information relay. The focus of this project is to assess the influence of disparate spatial representations on the human operator while executing sensor (i.e., camera) control.

In general, performance on spatial tasks worsens as a result of conflicting and/or inconsistent spatial representations. Shepard & Metzler (1971) used 3D objects to test peoples' ability to recognize new objects across different viewpoints and noted that participants performed faster when tested with the original learned view than with a new viewpoint. Moreover, they found that participants' reaction time was a linear function of the angle between learned and presented view – the greater the change in position, the slower the response. This oft-cited "mental rotation" task implicates some cognitive "cost" to mentally rotate an object. Could the mental processes underpinning the rotation task be similar to those utilized when a UAV sensor operator tracks a target? We predict that the mental processes are indeed similar and, thus, target tracking performance will decline while in an airborne environment.

The general finding of performance decrements due to mental manipulation of the spatial orientation of objects has been well-established over the past four decades. More recently, however, it has been determined to be subject to further distortions. For example, Simons & Wang (1998) discovered that the ability to assess the spatial configuration of objects is not merely dependent on the visual stimuli. They found that a viewpoint change does not impair the understanding of where objects are in relation to each other unless the viewpoint change is decoupled from a participant's control. In other words, when a participant changed their viewpoint by physically changing their position, their ability to detect subtle changes in the spatial configuration of objects around a table went unchanged. When the scene was moved independent of the participant's control, however, the ability to detect changes in the spatial layout of the objects was impaired. Similarly, Wraga, Creem-Regehr, and Proffitt (2004) found that the relative position of objects in a simulation was most accurately and quickly identified when the participant's motion was embedded within the simulation. (For further examples of the value of coupling movement and viewpoint, see Jürgens & Becker, 2011; Klatzky et al., 1998; Rokos-Ewoldsen et al., 1998; Simons, Wang, & Roddenbery, 2002; Wraga, Creem-Regehr, & Proffitt, 2000; and/or see Previc & Ercoline, 2004, for an overview of spatial disorientation in aviation.)

These effects have been shown to have real-world applicability as well. Muth, Walker, and Fiorello (2006) demonstrated that controlling one vehicle while riding in another reduced performance in their measure of accuracy; increased latency to complete their task; and resulted in a four-fold increase in motion sickness. This study used ground vehicles rather than aircraft, but clearly indicates that discordant spatial cues are a cause for concern. Similar findings have been discovered for tethered Remotely Piloted Vehicles (RPVs; see Hollands & Lamb, 2011).

Performance decline has also been noted for aviation tasks in spatially discordant environments. Reed (1977) demonstrated that simulated turbulence impaired control of a RPV.

Likewise, Olson and colleagues (2007) demonstrated that discordance between the platform motion and a controlled UAS significantly impairs performance. They conducted these experiments controlling a UAS simulator on a motion-platform (2006) and in an aircraft (2007), with vertical axis control and runway alignment impairments evident in both experiments. Additionally, their 2007 results suggest that the presence of horizon information creates greater impairment. Their methodology, however, was limited – participants were only seated in a forward configured seat in a civilian aircraft and only rudimentary maneuvers were used (e.g., turn, climb, and landing).

Due to these limitations, the current experiment included multiple seat configurations and a highly dynamic flight profile. In this experiment, participants used a joystick to track a vehicle traversing a specified path around the airfield at NAS Patuxent River, MD. The tracking crosshairs were depicted via a "camera" on a simulated UAV flying an elliptical flight pattern around the base (see Figure 1). The system recorded target tracking error while the participants attempted to maintain the cursor on the center of the simulated vehicle as it "drove" around the base (see Figure 2). In a counterbalanced design, trials took place at a desk (i.e., ground trials) and in the air flying a figure-eight flight profile while quickly ascending and descending in a P-3 (i.e., airborne trials).

The current experimental environment posed a unique problem to the visual and vestibular systems of the participants. Participants operated an unmanned aerial system sensor simulator while riding in the aft fuselage of a large military aircraft (i.e., P-3 Orion). During airborne trials, the aircraft flew alternating straight-and-level and highly dynamic flight profiles to induce variable magnitudes of spatial disparity between observed visual stimuli and perceived vestibular information. Consider the conflicting vestibular and visuospatial representations among the movement of the aircraft and ones' own position within the aircraft; the simulated UAS position and movement; and the ventral sensor (i.e., camera) position and orientation on the UAS. The translation and rotation difficulties within the aircraft (e.g., heave, sway, surge, pitch, yaw, roll) are easily and quickly resolved by most people, but an interesting problem arises when the participant is tasked to control a simulated camera on a simulated UAS that is in a different flight profile than they are experiencing. This task triples the degrees of freedom that must be resolved by the participant – the aircraft, UAS, and sensor all have their own six degrees of freedom.

To provide an example of multiple degrees of freedom for this experiment, envision the following: An aircraft is banking left and descending; the simulated UAS is banking right and ascending; and the camera is slewing aft - for a person in a starboard seat, facing towards the center of the aircraft, great discord between these spatial representations and their relevant sensory inputs would result. This creates the likelihood not only of noteworthy momentary performance lapses until these spatial discrepancies are reconciled, but also pervasive and sustained fatigue and motion sickness – not to mention the consequent creation of significant safety risks. In addition to the behavioral measures previously discussed, we administered the motion sickness assessment questionnaire (MSAQ) after ground trials and airborne trials to evaluate the effect of the multiple degrees of freedom on the well-being of the participants (see Appendix A).

Although this operational environment is quite unique, especially for experimentation, it should not be treated any different from other experimental environments (Gibson, 1966; Stroffregen & Riccio, 1988). In other words, the exceptionality of this operational environment elicits behavior specific to this environment as a result of the perceptual experience and, although unique, still provides meaningful information about conflicting spatial information resolution and motor behavior in a tracking task. This could be considered a limitation of the generalizability of the current study, but given the recent rapid advancement of technology in aviation, space, and underwater environments, value can be found through this examination of an infrequent environmental condition.

Through the use of this distinct experimental environment, we predict that when participants are airborne, their ability to track the target with the simulated UAV camera will not be as accurate or consistent via several measures. First, the error distance between the cursor and the target is predicted to be larger when participants are airborne than during ground trials. Second, the variability of the cursor movement about the center of the target is predicted to be higher during trials in the plane. Third, the amount of time on target (TOT), or when the cursor is within five meters of the center of the target, is predicted to be longer during ground trials than during airborne trials. Finally, we predict that self-reports of motion sickness will indicate higher magnitude of motion sickness during air trials than ground trials.

Method

Participants

Eight Naval Officers participated in this experiment. Participants had current flight physicals and were qualified to ride in military aircraft. These requirements were necessary given that data collection occurred on an aircraft during flight. All efforts to recruit an equal number of male and female participants were executed, but only males participated in this experiment - ages ranged from 33-49 ($M = 40.75$, $SD = 6.88$). Participants read and signed consent forms approved by the Naval Air Warfare Center – Aircraft Division Institutional Review Board (NAWC-AD IRB). Potential risks and their mitigations can be found in Appendix B.

Fortunately, none of these risks or discomforts occurred to the point that experimentation had to be paused or cancelled. Headaches and nausea were reported, but will be discussed later in the results section.

Materials

Four networked Dell Precision M6800 laptop computers (17.3” screen) presented the UAS sensor simulators to the participants. Three of the computers ran a modified version of MetaVR™ v5.10 Scenario Creation Tool (SCT), which is a 3D real-time PC-based virtual environment generator. This software was modified to generate the sensor information (i.e., camera) from the ventral side of a GlobalHawk UAS. The flight profile approximated that of the GlobalHawk, and maintained an unclassified level of fidelity.

The fourth computer ran the MetaVR™ v5.10 Virtual Reality Scene Generator (VRSG). This software generates surface information based on satellite information. Surface information of NAS Patuxent River, MD, was chosen because all participants were familiar with the geography and surface structures in and around this location. The fidelity of all visual stimuli approximated that of current (2014) video game technology.

Thrustmaster™ T-Flight Hotas X Flight Stick joysticks connected to the three participant computers. The default transfer function of the joystick to the cursor on the screen was non-linear, in that, small movements in the joystick moved the cursor to a lesser extent than larger joystick movements in a non-linear manner (i.e., sigmoidal transfer function). In other words, small joystick movements would not noticeably move the cursor, whereas long-distance cursor movement could be achieved easily without moving the joystick to its maximal range.

For this experiment, a Lockheed P-3 Orion provided the flight environment. The P-3 Orion is a four-engine turboprop aircraft developed for the United States Navy. Although normally used for anti-submarine or maritime surveillance missions, the aircraft used for this experiment had a nearly empty fuselage rather than the usual configuration for military operations. The empty fuselage allowed participants to walk freely in between trial runs and socialize away from the experimental set-up in the aft area (i.e., galley) of the aircraft. For inexperienced readers, the length of the aircraft is 116’ 10”, leaving ample room for movement of the participants.

Procedure

In a counterbalanced design, participants completed ground trials either before or after the airborne trials. Due to the small sample size, initial conditions were pseudo-randomly assigned between one condition and the other in the order that participants signed up for the study rather than through truly random assignment.

Regardless of initial condition assignment, each participant was trained to criterion on one of the laptop-based UAS sensor operator simulators. Criterion is a performance measure that is based on an individual’s performance, not a predefined level of proficiency. This simulation training occurred on the ground and included a basic introduction to the system displays and controls and an explanation of the mission. As previously mentioned, the mission was to keep crosshairs of a UAS sensor on a simulated ground vehicle driving a pre-programmed path around a local military base.

For ground trials, participants chose a one-hour time period that suited their schedule within one week prior or after airborne testing depending on their initial condition assignment. Participants were seated in front of one of the UAS sensor operator laptops and they completed approximately 30-45 minutes of trials that lasted approximately 1-2 minutes each.

At the beginning of each trial, the participant began with their “camera” fully zoomed-out in an attempt to prevent participants from easily replicating motor behavior to move the cursor over the target vehicle. Once the participant indicated that they were ready for the trial to begin, they were instructed to “zoom in” their camera to find the target vehicle and to keep the cursor on the center of the target as best they could. When the participant moved the cursor over the target vehicle, the researcher began a one-minute timer to designate the duration of a trial. After a minute of target tracking elapsed, the trial was over and the participant was instructed to zoom out their camera and wait for the next trial to begin. Upon completion of the ground trials, the participants were administered the MSAQ for comparison with the airborne trials. We implemented the same procedure for airborne trials, but with a few key differences.

After take-off, the Principle Investigator set-up three test stations in the aft area of the P-3 aircraft. This area is where the galley (i.e., kitchen) is located and contains bench seating at a large table and mounted stool seating at a small table. This seating configuration provided space for three participants to be run at a time in three different seating orientations: forward, backward, and center of the aircraft facing outboard. In addition to seating configuration, pilots flew two different flight profiles.

The first flight profile, Profile Alpha, was a standard racetrack (i.e., oval) profile flown at one altitude. The second flight profile, Profile Beta, was a figure eight path flown in a 2000 feet per minute ascending and descending pattern. Two groups of three and one group of two participants completed 30 trials each. The Principal Investigator communicated with the pilots via electronic means to indicate when to change from Profile Alpha to Profile Beta – this manipulation was counterbalanced among the groups of participants as well.

Data Analyses

Analyses included data from all eight participants – no adverse events or instructions misunderstandings required any data exclusions.

Residual distribution and link-function assignment to transform the data to a normal distribution were identified with Box-Cox analysis, and planned analyses were conducted with linear-mixed effects modeling (LME) in R (available at www.r-project.org) using the lme4 package (Nelder & Wedderburn, 1972). Graphical representations of the data were produced in R, Microsoft Excel, and JMP v9, a graphical analysis product developed by SAS.

Two within-subject variables (e.g., baseline/airborne trials, elapsed time) and one between-subject variable (e.g., seat configuration) were used as model predictors for three dependent variables (e.g., tracking error, tracking variability, proportion of time on target). Student's t-test analyses of the MSAQ data were conducted as well.

Residual distributions for tracking data were positively skewed, indicating that participants were more often near the target than far away from the target in both airborne and ground trials (see Figures 3 & 4). A Box-Cox analysis indicated that a modified log-transform normalized the distributions (see Figures 5 & 6). After data normalization, LME analyses revealed that the experimental manipulations influenced the participants' ability to track targets. Results are written in a manner analogous to simple-effects effects tests to ease interpretation for the reader.

Results

Flight profile influenced tracking performance [$t=18.83$, $p<.001$]. Post-hoc analyses revealed that all three trial types resulted in significantly different tracking performance of the participants. Ground trials resulted in the lowest tracking error, followed by trials conducted during Profile Alpha, and trials conducted during Profile Beta resulted in the worst tracking performance of the participants (see Figure 7).

Further analyses of tracking performance revealed that seat position also influenced tracking performance [$t=-6.48$, $p<.01$]. Post-hoc analyses indicate that the best tracking performance was found during ground trials, forward and aft seating positions were significantly worse, and, surprisingly, an outboard-facing orientation resulted in the worst tracking performance (see Figure 8). Although we did not assign specific hypotheses to seat configuration as a predictor of performance, these results suggest that further investigation is needed and will be discussed further in the next section.

Our second hypothesis predicted that the variability of cursor movement about the center of the target would be higher during airborne trials than ground trials. This relationship was found to be true, but there was a significant interaction between trial type and trial number for the variability of tracking performance [$t=-18.01$, $p<.001$]. This interaction reveals that although performance during airborne trials began more variable at the beginning of a block of data collection, performance became more stable as the experiment progressed.

Next, we predicted that participants would spend less time on target (TOT) during airborne trials than during ground trials. An interaction of trial type and trial number predicted TOT performance [$F(2,2) = 47.15$. $p<.001$]. As predicted, TOT was worse during airborne trials, but only initially. Similar to tracking variability, as trials progressed TOT increased for airborne trials. Notably, however, TOT performance during ground trials decreased as trials progressed (see Figure 10).

Finally, participants indicated that symptoms of motion sickness were more prevalent during airborne trials than during ground trials [$F(1,14) = 4.70$, $p<.05$] (see Figure 11).

Headaches, fatigue, and nausea were the most common symptoms to become more pronounced during airborne trials.

Discussion

This experiment investigated the effects of multiple disparate sources of spatial information on motor tracking behavior. The environment in which this experiment occurred was novel and highly dynamic causing mismatched information from the visual and vestibular systems to negatively influence tracking performance and overall comfort of the participants. Due to the uniqueness of this testing environment, some may ask about the utility of the project – how are these findings extensible or applicable in other, not so novel, environments?

At first glance, one may be inclined to side with the previously mentioned skeptical reader, but after reviewing the results of the current study, this section will outline other military applications and provide further questions that are better suited for the laboratory. The results generally supported the hypotheses posited for this study and some unexpected findings came to light as well.

We asserted that flight condition (i.e., ground/airborne) would influence tracking performance and found that not only were differences in performance found between the baseline (i.e., ground) and testing (i.e., airborne) trials, but the phase of flight (i.e., Profile Alpha, Profile Beta) also resulted in performance differences. These results suggest that not only does highly dynamic motion negatively influence tracking performance, but fairly inert, stable motion can similarly lead to poorer tracking performance.

During analyses of tracking performance, we noticed fairly obvious differences based on seat orientation. Although we did not address this topic as an original hypothesis due to a lack of existing evidence in distinguishing between forward, backward, or side-facing orientation in performance metrics, we decided to further scrutinize these differences. Similar to the first hypothesis, performance during ground trials was better than during airborne trials, but facing outboard during testing resulted in poorer tracking performance than facing either forward or aft. No interactions with seat orientation were found, but due to the small number of participants, it would not be surprising to find more interesting results that could elucidate the relationship of motion and spatial orientation with a larger number of participants.

While not a significant difference, outboard-facing participants tended to report higher levels of headaches and nausea than forward or aft facing participants. Perhaps this unnatural traversing of space induces more spatial discordance than more natural forward or backward motion. To the uninformed reader, the solution to this issue seems simple – don't orient seats facing inboard or outboard. It should be noted, however, that most military aircraft have side-oriented payload operator seats to save space within the aircraft. Therefore, it is cost-prohibitive to suggest reconfiguration of seating across hundreds of aircraft as a solution. In the next few paragraphs, we will discuss results that suggest perhaps training or repeated exposure to conflicting spatial information may result in performance analogous to baseline conditions, which is a much less costly solution.

We predicted that tracking performance would be more variable while airborne than during ground trials. For the beginning of each data collection session while airborne, we found this relationship to be true – performance was more variable while airborne than during ground trials. As time progressed, however, performance variability returned to a profile similar to that of baseline. Would this initial increase in variability persist over time, or would repeated exposure eliminate variable tracking performance?

Another interaction resulted between time on target (TOT) and trial number. As previously mentioned, TOT is when the crosshair was within 5 meters of the center of the tracking target. This interaction revealed that as time passed, TOT was initially highest during ground trials; initially lowest during Profile Beta (i.e., highly dynamic); and TOT was stable during Profile Alpha (i.e., not dynamic). Interestingly, during Profile Beta, performance became less variable and TOT increased as the experiment progressed, and the opposite relationship was found to be true for ground trials. The former result suggests that exposure to high motion environments while performing motor skill tasks warrants further investigation. Whereas the latter is indicative of task boredom; a more thorough investigation of this performance decrement should be considered as well.

Finally, as expected, participants reported higher levels of motion sickness during airborne flights than during ground trials. Although these results could be confounded by demand characteristics of the experiment, the increased trend was only found in a subset of questions. In particular, questions involving headache, nausea, and fatigue indicated an increase in magnitude while other questions of perspiration, anxiety, and mood remained stable. Since an increase across all measures was not found, we can conclude that participants answered the MSAQ in a manner consistent with their self-assessment and not due to demand characteristics.

Although this project took place in a difficult to access and highly specific environment outside of the laboratory, the lessons learned are extensible to other more highly controlled environments. For example, pilot studies for this project took place in a flight simulator with a 6-DOF (i.e., degrees of freedom) motion base. This environment provided discrepant vestibular and visual information to the participants without requiring access to a large experimental aircraft – the results of the pilot studies were similar, but performance degraded to a smaller magnitude. We expect to see further research in similar environments to investigate the effect of repeated exposure in dynamic motion environments to evaluate if training is sufficient to overcome performance changes and motion sickness.

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Appendix A

MOTION SICKNESS ASSESSMENT QUESTIONNAIRE (MSAQ)

Instructions. Using the scale provided above each statement, please rate how accurately the following statements describe your experience.

Not at all Severely
1——2——3——4——5——6——7——8——9
I felt sick to my stomach.

Not at all Severely
1——2——3——4——5——6——7——8——9
I felt faint-like.

Not at all Severely
1——2——3——4——5——6——7——8——9
I felt annoyed/irritated.

Not at all Severely
1——2——3——4——5——6——7——8——9
I felt sweaty.

Not at all Severely
1——2——3——4——5——6——7——8——9
I felt queasy.

Not at all Severely
1——2——3——4——5——6——7——8——9
I felt lightheaded.

Not at all Severely
1——2——3——4——5——6——7——8——9
I felt drowsy.

Not at all Severely
1——2——3——4——5——6——7——8——9
I felt clammy/cold sweat.

Not at all Severely
1——2——3——4——5——6——7——8——9
I felt disoriented.

Not at all Severely
1——2——3——4——5——6——7——8——9
I felt tired/fatigued.

Not at all Severely
1——2——3——4——5——6——7——8——9
I felt nauseated.

Not at all Severely
1——2——3——4——5——6——7——8——9
I felt hot/warm.

Not at all Severely
1——2——3——4——5——6——7——8——9
I felt dizzy.

Not at all Severely
1——2——3——4——5——6——7——8——9
I felt like I was spinning.

Not at all Severely
1——2——3——4——5——6——7——8——9
I felt as if I may vomit.

Not at all Severely
1——2——3——4——5——6——7——8——9
I felt uneasy.

Appendix B

Several potential risks and discomforts existed for participants. These risks and discomforts and their potential mitigations are listed below:

Spatial Disorientation - the inability to correctly interpret aircraft attitude, altitude or airspeed, in relation to the Earth or point of reference, especially after a reference point (e.g., the horizon) has been lost. Spatial disorientation can escalate from a novel and interesting experience (e.g., amusement park rides) to a quite uncomfortable experience. If a participant experienced extreme disorientation to the point of discomfort, the experiment would have been temporarily stopped while the participant regained a point of reference to regain spatial orientation. If they chose to end their participation in the experiment, the aircraft would have returned to base and testing for that participant would have finished.

Nausea - a very common symptom that is often described as a feeling of queasiness or wooziness, or a need to vomit. If a participant needed to vomit, a proper receptacle would have been provided. The experiment would have been temporarily stopped while the participant took measures to relieve their nausea. If they chose to end their participation in the experiment, the aircraft would have returned to base and testing for that participant would have finished.

Hyperhidrosis - condition characterized by abnormally increased sweating/ perspiration in excess of that required for regulation of body temperature. This secondary effect of spatial disorientation and/or nausea is benign and no extraneous prevention or treatment was necessary.

Headache - pain anywhere in the region of the head or neck. If a participant experienced headache, the experiment would have been temporarily stopped while the participant took measures to relieve their headache. If they chose to end their participation in the experiment, the aircraft would have returned to base and testing for that participant would have finished.

Flight Mishap (including injury or death) - an occurrence associated with the operation of an aircraft, which takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked, where a person is fatally or seriously injured, the aircraft sustains damage or structural failure or the aircraft is missing or is completely inaccessible. All safety measures and training were completed by all aircrew aboard the aircraft prior to flight.

Figure Captions

Figure 1. View from simulated UAV at 10,000'. Trials begin in "zoomed-out" camera position to vary cursor starting position which eliminates rote motor movements.

Figure 2. "Zoomed-in" view of trial where cursor is approximately 45^0 off target in the center of the screen. Note that Figure 2 is a zoomed-in image of Figure 1.

Figure 3. Distribution of residuals for distance from target for airborne trials indicate a strong positive skew in the distribution. This distribution suggests participants kept the cursor closer to the target for more time than farther distances.

Figure 4. Log transform of the distribution of residuals for distance from target for airborne trials normalizes the data for analyses.

Figure 5. Distribution of residuals for distance from target for ground trials indicate a strong positive skew in the distribution. This distribution suggests participants kept the cursor closer to the target for more time than farther distances.

Figure 6. Log transform of the distribution of residuals for distance from target for ground trials normalizes the data for analyses.

Figure 7. Ground trials produced the least error distance from the target center. Profile Alpha (e.g., racetrack) trials led to significantly worse tracking than ground trials, and Profile Beta (e.g., dynamic) trials led to the worst average tracking performance of participants.

Figure 8. Inboard-facing seat orientation resulted in the worst tracking performance. Forward and aft seating resulted in significantly better performance, and ground trials resulted in the best tracking performance.

Figure 9. An interaction of trial type and trial number for tracking variability indicates that although tracking performance is initially more variable during airborne trials, it stabilizes and returns to baseline variability levels as trials progress.

Figure 10. The proportion of time on target (i.e., within 5 meters) was determined by trial type and trial number. Performance improved for participants while airborne, but degraded during ground trials as trials progressed.

Figure 11. Participants indicated a higher magnitude of motion sickness symptoms during airborne trials than during ground trials.

Figure 1.

Figure 2.

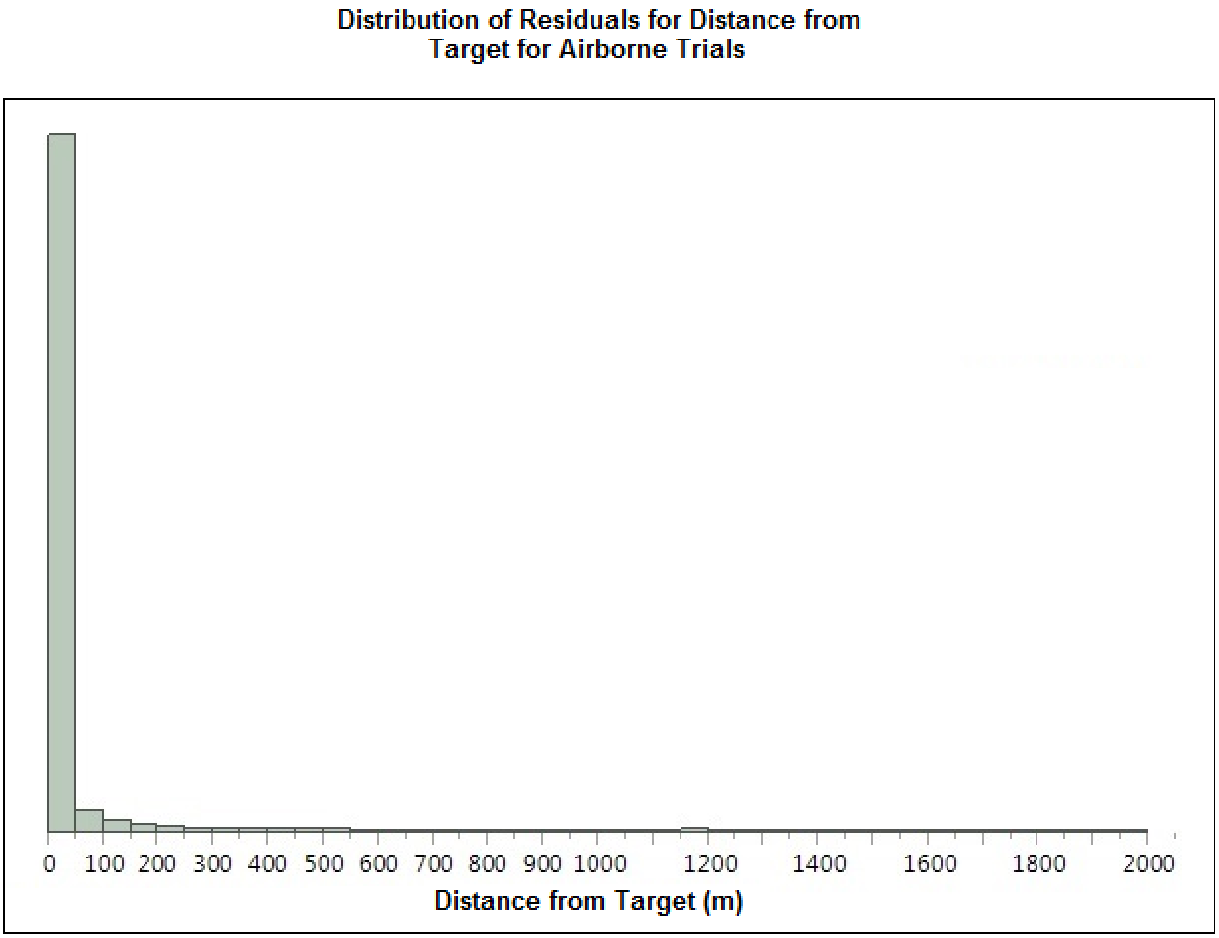

Distribution of Residuals for Distance from Target for Airborne Trials
0
100
200
300
400
500
600
700
800
900
1000
1200
1400
1600
1800
2000
Distance from Target (m)

Figure 3.

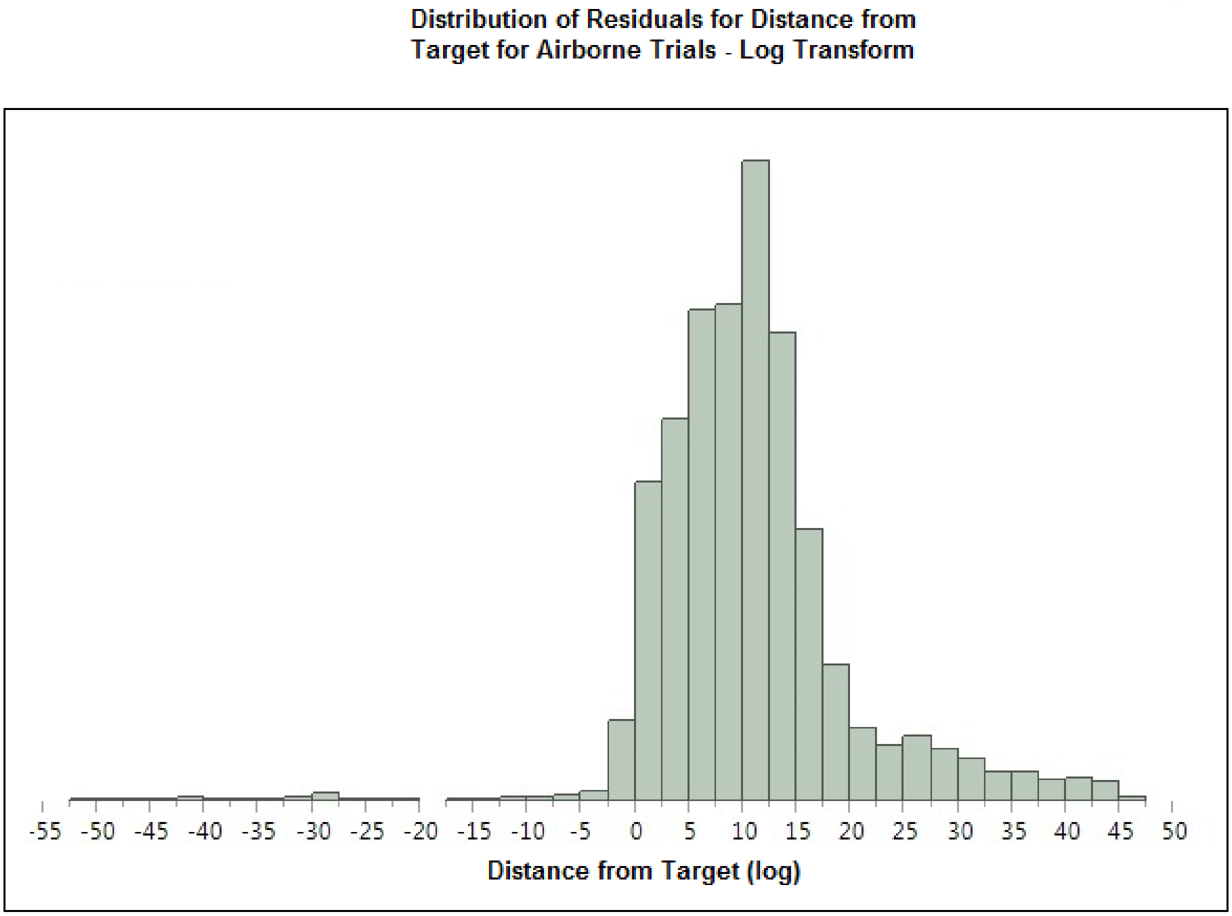

Distribution of Residuals for Distance from Target for Airborne Trials - Log Transform
-55 -50 -45 -40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40 45 50
Distance from Target (log)

Figure 4.

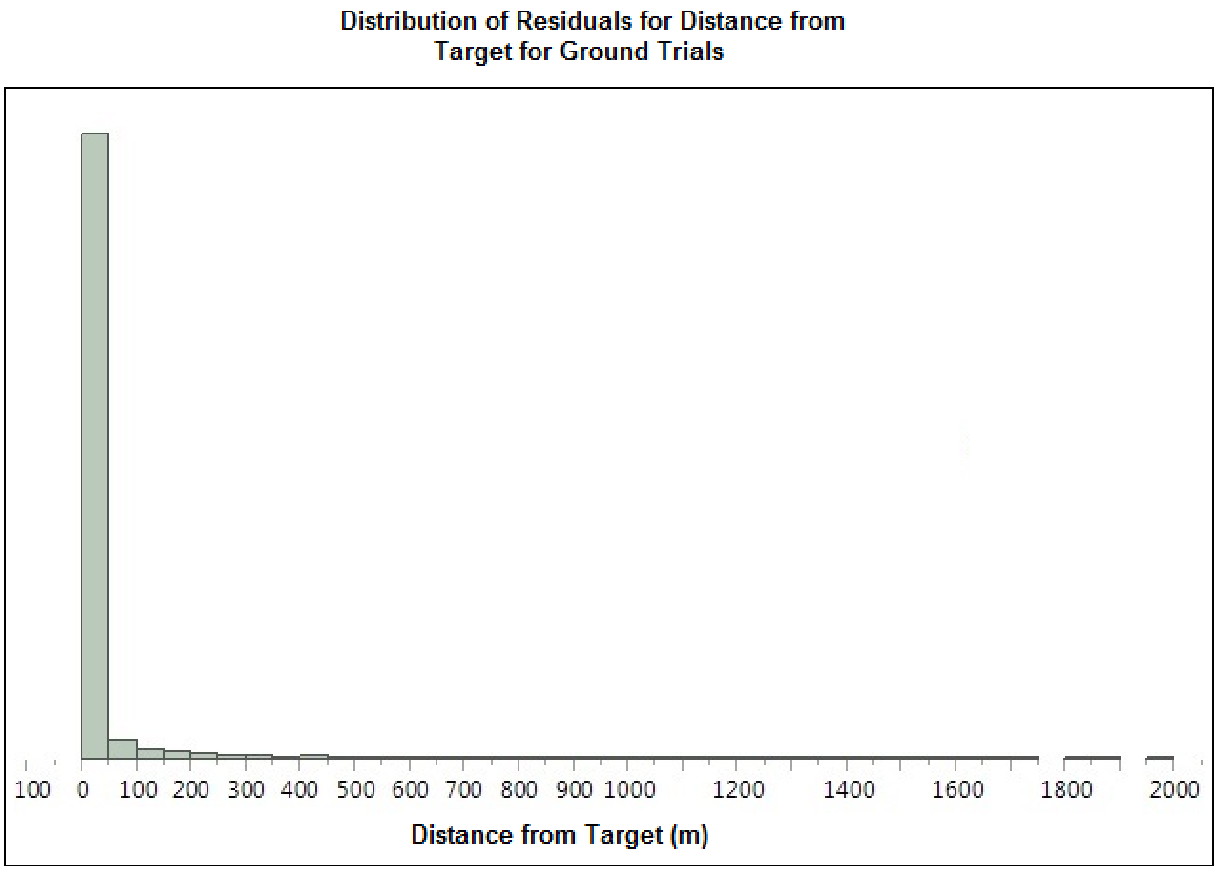

Distribution of Residuals for Distance from Target for Ground Trials
100
0
100
200
300
400
500
600
700
800
900
1000
1200
1400
1600
1800
2000
Distance from Target (m)

Figure 5.

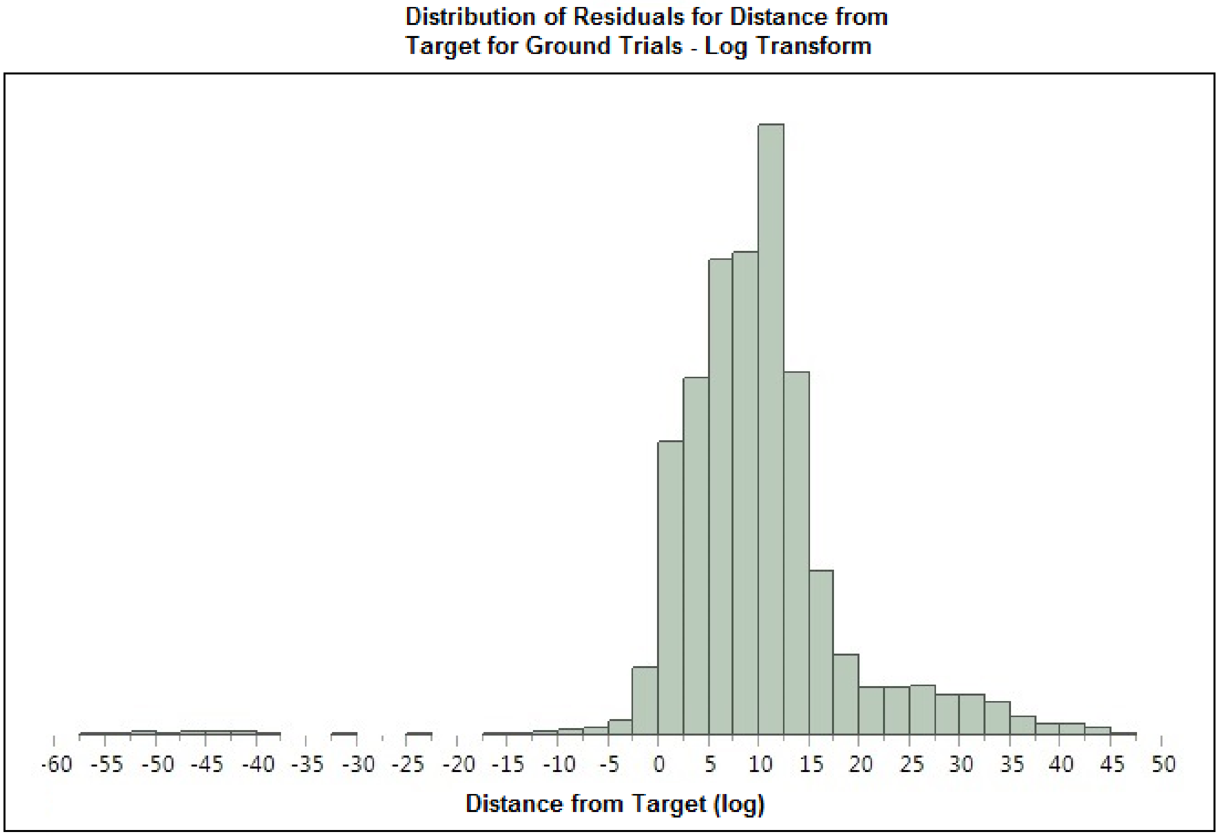

Distribution of Residuals for Distance from
Target for Ground Trials - Log Transform
-60 -55 -50 -45 -40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40 45 50
Distance from Target (log)

Figure 6.

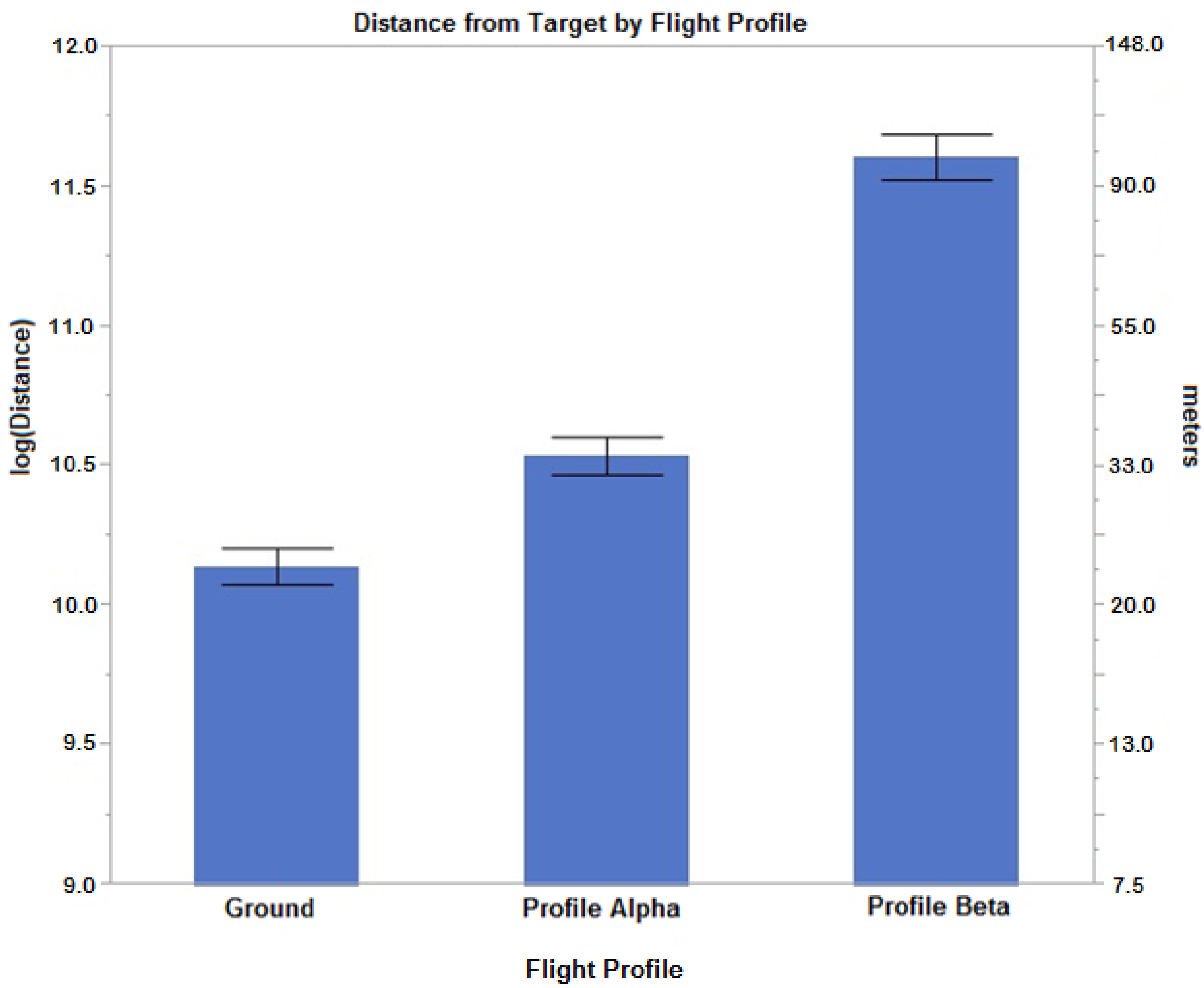
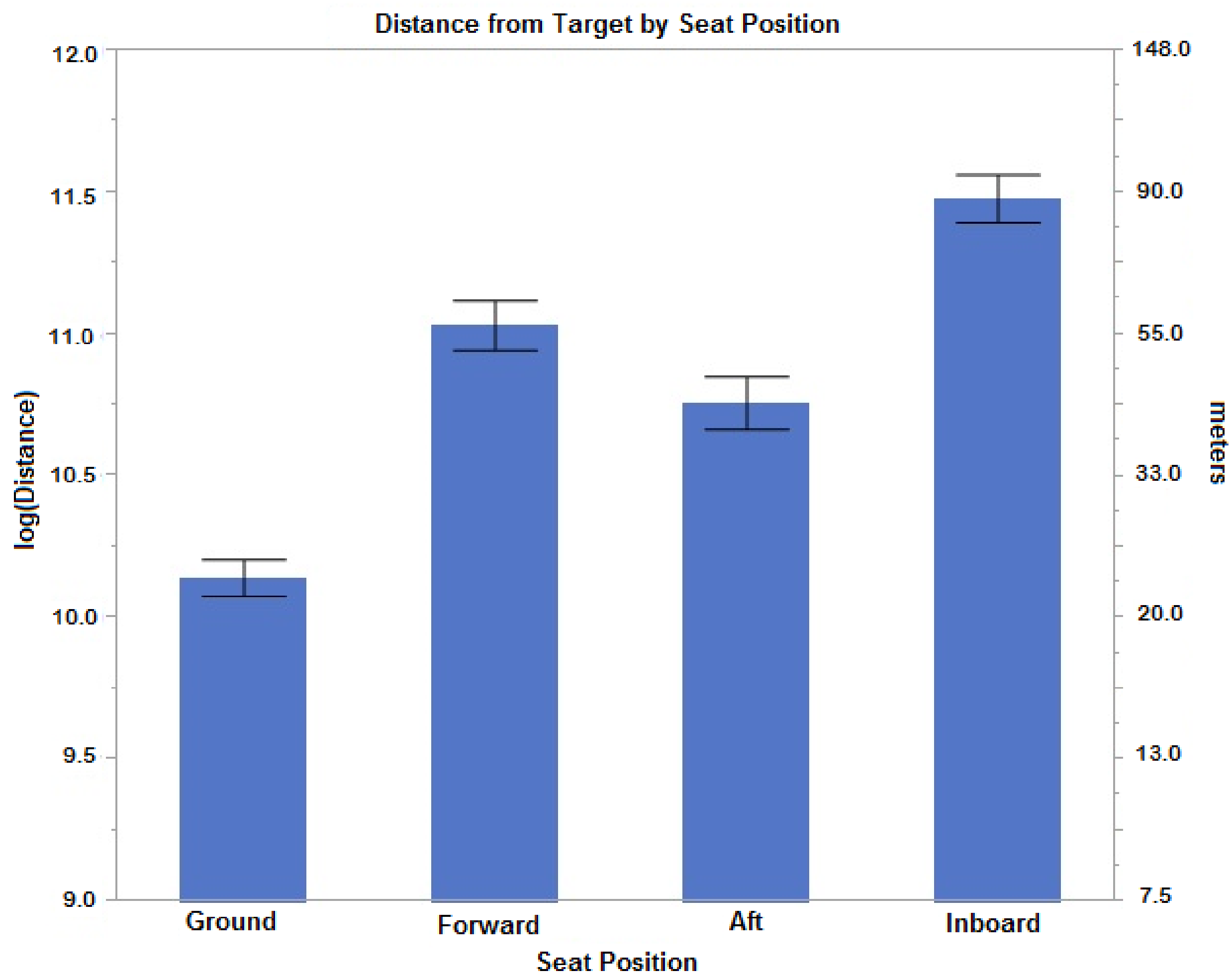

Distance from Target by Flight Profile
12.0
11.5
11.0
10.5
10.0
9.5
9.0
log(Distance)
148.0
90.0
55.0
33.0
20.0
13.0
7.5
meters
Ground
Profile Alpha
Profile Beta
Flight Profile

Figure 7.



Distance from Target by Seat Position
12.0
11.5
11.0
10.5
10.0
9.5
9.0
log(Distance)
148.0
90.0
55.0
33.0
20.0
13.0
7.5
meters
Ground
Forward
Aft
Inboard
Seat Position

Figure 8.

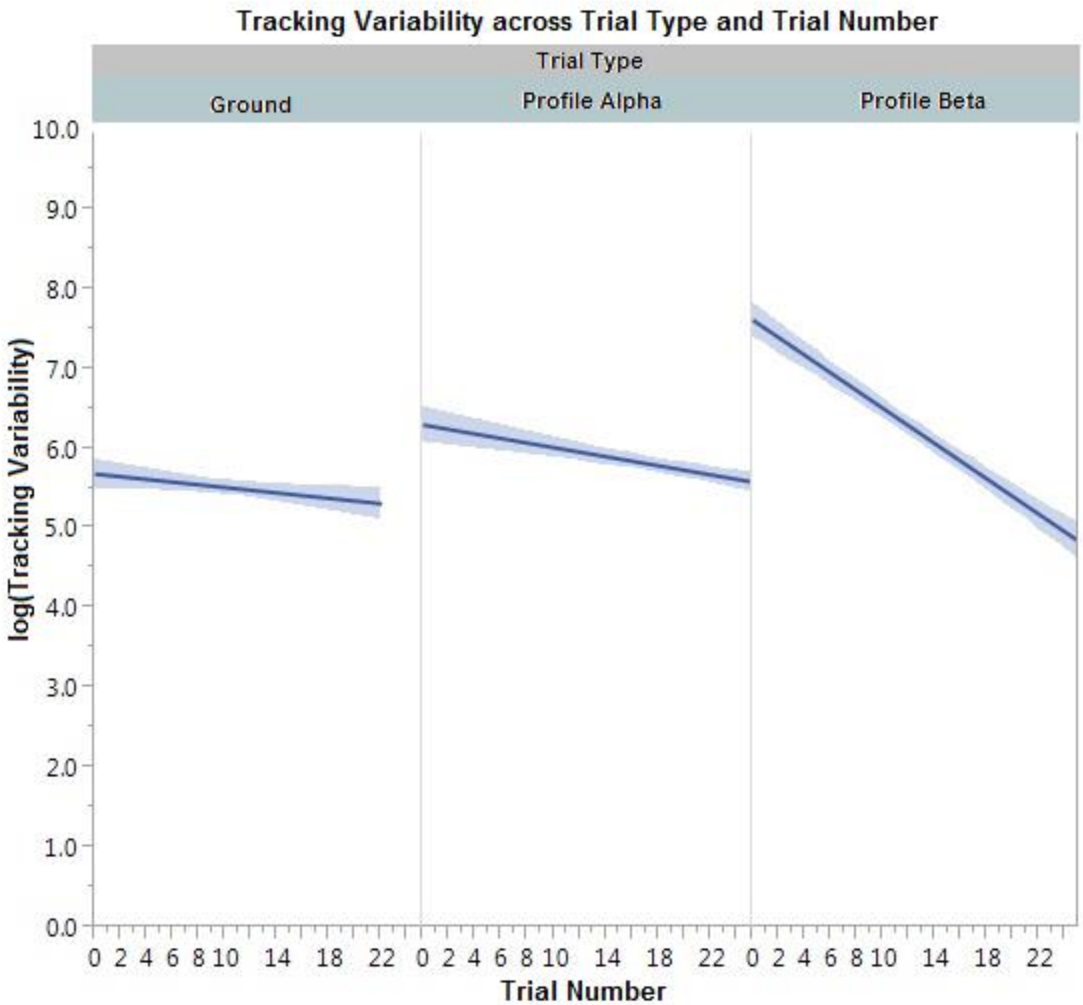

Tracking Variability across Trial Type and Trial Number
Trial Type
Ground
Profile Alpha
Profile Beta
log(Tracking Variability)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0 2 4 6 8 10 14 18 22 0 2 4 6 8 10 14 18 22 0 2 4 6 8 10 14 18 22
Trial Number

Figure 9.

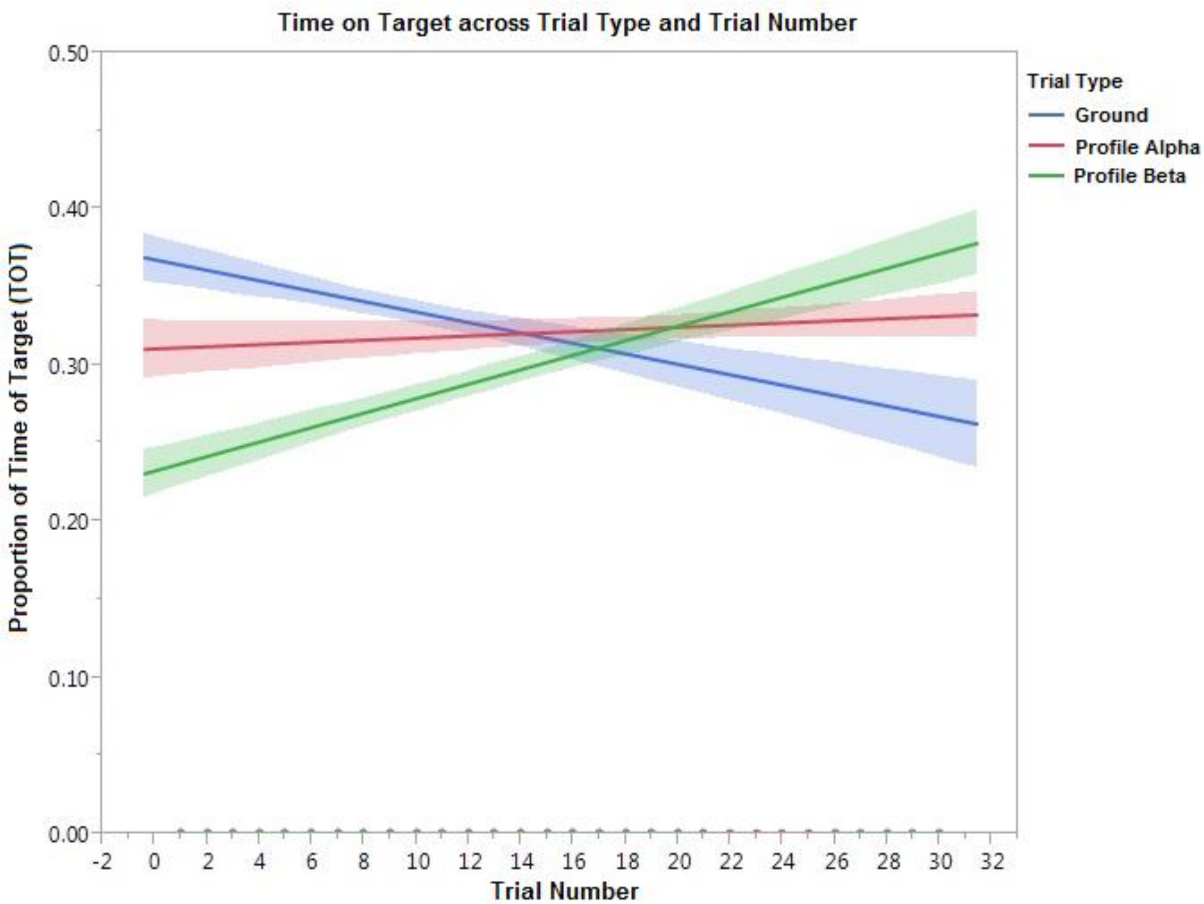

Time on Target across Trial Type and Trial Number
Trial Type
Ground
Profile Alpha
Profile Beta
Proportion of Time of Target (TOT)
0.50
0.40
0.30
0.20
0.10
0.00
-2
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
Trial Number

Figure 10.

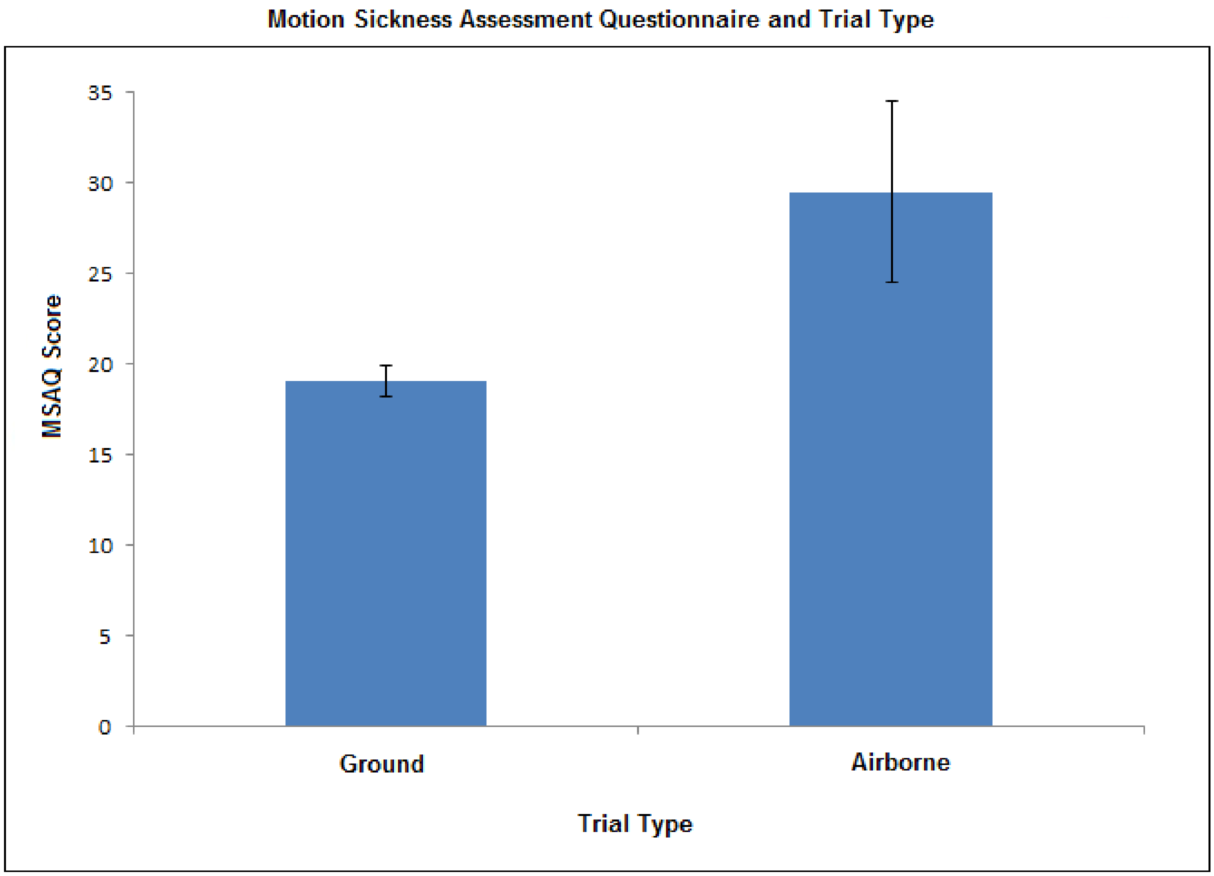

Motion Sickness Assessment Questionnaire and Trial Type
MSAQ Score
35
30
25
20
15
10
5
0
Ground
Airborne
Trial Type

Figure 11.